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Di-pion System in the Reaction $\pi^- p \to n\pi^0\pi^0$ at 1.6 to 2.4 GeV/c*

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We report results from a high-statistics study of the reaction $\pi^- p \to n\pi^0\pi^0$ between 1.6 and 2.4 GeV/c, in which *all* the final-state particles were detected. The $2\pi^0$ mass spectrum exhibits a marked enhancement in the region of 800 MeV, which is narrower in width than predicted by the recently reported "down-down" solution for $I=0$, S-wave, π-π phase shifts.

In principle, the study of the isoscalar ($I=0$) dipion system below 1-GeV $\pi\pi$ mass is simplified by analyzing the $2\pi^0$ system, from which the effects of the $I=1$ $\rho(765)$ are excluded.[1] However, because of the complexity of detecting and measuring the kinematics of neutral particles, experiments which study reactions such as

$$\pi^- p \to n\pi^0\pi^0 \tag{1}$$

have yielded inconsistent results.[2,3]

We report results from a high-statistics experiment, performed at the Berkeley Bevatron, to study Reaction (1) at beam momenta of 1.59 to 2.39 GeV/c in 0.20-GeV/c intervals.[4] The prominent features of the experiment which minimized the systematic biases are the following:

(1) Identification of the final state by detecting the neutron and *all* the γ rays from the π^0 decays. The kinematic variables of *each* of the particles were measured and an overconstrained (6-constraint, 3-vertex) kinematic fit was made to each event, using a modified version of the Lawrence Berkeley Laboratory bubble-chamber program SQUAW.[5]

(2) A high γ-ray detection efficiency over more than 90% of the entire 4π-sr lab solid angle.

(3) An empirical check of systematic effects by comparing the differential cross sections for the two-body final states, $n\pi^0$ and $n\eta$, measured with and without the neutron detector in the triggering logic.

The experimental setup is the same as described in a previous paper,[6] except for the addition of the neutron detector.[7] This detector consisted of twenty cylindrical plastic scintillation counters, each 8 in. in diameter and 8 in. long, located 15 ft from the target and subtending polar lab angles (θ_n) from 12 to 72 deg with respect to the central beam ray. Each neutron counter had an additional counter mounted in front of it to veto charged particles. The neutron trigger was set to accept neutrons of velocity (β) in the re-

TABLE I. Cross sections for $\pi^- p \to n\pi^0\pi^0$.

P_{π^-} (GeV/c)	Total (μb)	$-t \leq 0.3$ (GeV/c)^2 [a] (μb)
1.59	1310 ± 100	325 ± 30
1.79	1360 ± 100	430 ± 30
1.99	1390 ± 90	335 ± 30
2.19	1380 ± 90	320 ± 30
2.39	1140 ± 70	225 ± 15

[a] Δ cut corrected for by the ratio of phase space with and without Δ mass bands.

gion $0.17 \leq \beta \leq 0.84$, corresponding to invariant four-momentum transfers to the nucleon $(-t_{p\to n})$ of 0.029 to 1.54 (GeV/c)^2. The neutron timing resolution was ±0.6 nsec.[7]

Data were collected in two different modes of electronic triggering conditions: (1) a neutron counter signal in coincidence with a neutral-final-state trigger, and (2) a neutral-final-state trigger only. The latter data were used to determine partial cross sections for various neutral final states, as described by Nelson.[8] Cross sections for Reaction (1) are listed in Table I. They agree well with those of Crouch *et al.*[9]

The study of the dynamical properties of Reaction (1) was made with the neutron-trigger data sample containing four visible showers in the spark chambers and no upstream shower-counter signal. The γ-ray energy measurement from spark counting was calibrated by an overconstrained kinematic fit of the two-shower events to $n\pi^0$ and $n\eta$ final states. The four-shower data sample consists of about 7400 events that fit Reaction (1) with a χ^2 probability of $\geq 5\%$. The data within the neutron-counter acceptance region in t and θ_n have been corrected for neutron scattering in the chambers, neutron-counter geometry, and detection efficiency.[7] Structure is evident in both the $n\pi^0$ and $\pi^0\pi^0$ mass plots. The dominant feature, at all values of t, is the peak in the $n\pi^0$ spectrum (not shown) corresponding to $\Delta^0(1236)$ production.[10] To isolate the $2\pi^0$ system from the effects of the $\Delta(1236)$, we cut out all events having at least one $n\pi^0$ combination in the broad mass band of 1100 to 1300 MeV. The $n\pi^0$ mass spectrum of the surviving events exhibits no resonant structure.

Figure 1 displays the combined data from the five beam momenta, with the Δ-band events excluded. The t distribution [Fig. 1(a)] is characterized by a pronounced peak at low t. The curve represents the prediction of "peripheral phase space" (PPS) which is defined as (phase space) $\times(-t)/(t-\mu^2)^2F(t)$, where μ is the pion mass and $F(t)$ is the Dürr-Pilkuhn vertex factor[11] multiplied by Wolf's t-dependent form factor.[12,13] This expression, normalized to the number of events below 1 GeV di-pion mass, fits the t distribution very well in the peripheral region, $-t \leq 0.3$ (GeV/c)^2.

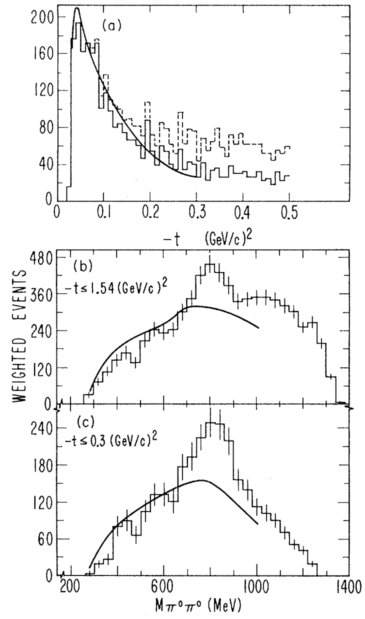

FIG. 1. Data with $\Delta(1236)$ mass-band events excluded (see text). (a) t distribution. Solid (dashed) histogram, $M_{\pi^0\pi^0} < 1000$ MeV (< 1400 MeV). Curve, PPS for $M_{\pi^0\pi^0} < 1000$ MeV, normalized to the data in the solid histogram for $-t \leq 0.3$ (GeV/c)^2. (b), (c) $2\pi^0$ mass spectrum for the t region indicated. Curve in (b), combination of phase space and PPS (see text); (c), PPS only. Both curves are normalized to the corresponding data below 1000 MeV but outside the 700–900-MeV region.

Figure 1(b) shows the $2\pi^0$ mass spectrum for the entire t region (4088 events). The mass resolution is approximately ±35 MeV half width at half-maximum. A marked enhancement in the 800-MeV region is clearly evident. The curve represents a crude approximation of the spectrum as the sum of phase space and PPS, the relative amounts being determined by a maximum-likelihood fit to the t distribution and the mass spectrum at each momentum. Figure 1(c) shows the mass spectrum (1323 events) for events with $-t \leq 0.3$ (GeV/c)^2. The same structure is much more pronounced here, because the production of the enhancement is more peripheral than that of the background. The curve represents the PPS distribution normalized to the data below 1000 MeV but excluding the 700- to 900-MeV region.

The di-pion-decay angular distribution was studied with respect to the incident π^- direction in the di-pion rest frame for events in the peripheral region. For all $2\pi^0$ masses below about 940 MeV, the decay distribution was consistent with isotropy outside the region corresponding to the Δ-mass-band cut and hence is consistent with spin $J=0$ for the di-pion system.

To parametrize the peripheral data we assume the one-pion-exchange mechanism as a production model, using the Chew-Low equation[14] modified by the form factor $F(t)$ defined above, and work in the physical region (since there are too few events to make a meaningful extrapolation to the pion pole). Cross sections (Table I) for this t cut were determined by normalizing the neutron-counter data to the total $n\pi^0\pi^0$ cross sections, as outlined in Ref. 7. In the S-wave approximation, the $\pi\pi$ cross section is proportional to $\sin^2(\delta_0{}^0 - \delta_0{}^2)$, where $\delta_0{}^0$ ($\delta_0{}^2$) is the $I=0$ ($I=2$) S-wave phase shift. The effect of the $\Delta(1236)$ cut is only to eliminate a well-defined region in the di-pion-decay angular distribution and is accounted for in the present analysis.[7] Details of the calculation are given elsewhere.[15]

A weighted average of $\sin^2(\delta_0{}^0 - \delta_0{}^2)$ from the five beam momenta is plotted as a function of $m_{\pi\pi}$ in Fig. 2. The error bars in each bin are purely statistical and do not include a systematic uncertainty in the overall normalization (± 6%) from our $n\pi^0\pi^0$ cross-section determination for $-t \leq 0.3$ $(\mathrm{GeV}/c)^2$. Our analysis does not extend beyond the di-pion mass of 940 MeV because of the presence of the D-wave contribution whose amount is difficult to determine because of the $\Delta(1236)$ cut.

Although our phase-shift results are derived from a particular one-pion-exchange production model with some inherent limitations (described, for example, by Kane in Ref. 1), it is useful nonetheless to compare the general features in Fig. 2 with the recent results of Protopopescu *et al.*[16] from their analysis of the $\pi^+\pi^-$ system. Their "down-up" solution is clearly in disagreement with our data and can be ruled out completely—a conclusion consistent with that of Ref. 16. Within the normalization uncertainty, our results agree quite well with the "down-down" solution for $M\pi^0\pi^0 \gtrsim 800$ MeV. Below this mass, our values of $\sin^2(\delta_0{}^0 - \delta_0{}^2)$ appear to drop more rapidly with decreasing $\pi\pi$ mass than do those of the down-down solution.

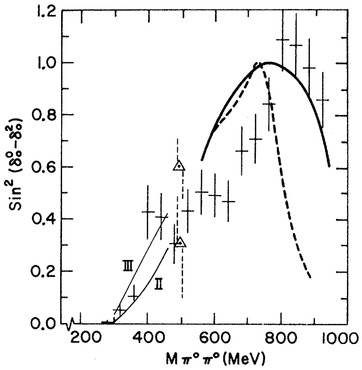

FIG. 2. Phase-shift results. Solid (dashed) curve above 550 MeV, "down-down" ("down-up") solution from Ref. 16. Curves II and III are solutions II and III, respectively, from Ref. 17. The corresponding S-wave scattering lengths ($a_s{}^I$), in units of $m_\pi{}^{-1}$, are $a_s{}^0 = 0.16$ and $a_s{}^2 = -0.048$ for solution II and $a_s{}^0 = 0.60$ and $a_s{}^2 = 0.043$ for solution III. Dashed points at the K mass, Ref. 18.

The same conclusions follow if we compare only the shape of the mass spectrum in Fig. 1(c) with the shape predicted from the phase shifts of Ref. 16, using the Chew-Low equation[14] modified by $F(t)$. The predicted shape is relatively insensitive to the choice of form factor, provided it fits the t distribution [Fig. 1(a)]. The observed enhancement at 800 MeV is narrower than that predicted by the down-down solution; however, the falloff on the high-mass side of the enhancement is consistent with the prediction. The enhancement is also narrower than that observed in a recent experiment[3] at 8 GeV/c.

Finally, we also show in Fig. 2 the two phase-shift solutions at the K mass obtained by Sarker[18] from an analysis of $K \to 2\pi$ decays and the theoretical solutions (curves II and III) by Basdevant *et al.*[17] for the phase shifts just above threshold. Neither solution can be ruled out by our results.

Note added.—In a very recent $\pi\pi$ phase-shift analysis by Estabrooks *et al.*[19] the authors present two solutions for $\delta_0{}^0$ in the region $M_{\pi\pi} = 450$–1000 MeV. They conclude that solution 1 is the correct one when compared with the shape of the $\pi^0\pi^0$ mass spectrum of Ref. 3. On the other hand, our results in Fig. 2 are consistent with solution 2 below the point where the two solutions cross over at $M_{\pi^0\pi^0} = 770$ MeV, and solution 1 above this crossover point. However, the validity of jumping from one solution to the other at the crossover point may be questioned.[19]

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SU(3) Symmetry in Electron-Positron Annihilation

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Exact SU(3) predicts equal production of $\pi^+\pi^-$ and K^+K^- final states, while $K^0\bar{K}^0$ is forbidden as a result of cancelation between isovector and isoscalar photon contributions. Symmetry breaking destroys coherence between ρ-, ω-, and φ-like photon components. Branching ratios $\pi^+\pi^-/K^+K^-/K^0/\bar{K}^0$ calculated under various coherence assumptions give different results. Experimental measurements should test this interference and give insight into the role of photon SU(3) structure in deep annihilation.

The assumption of SU(3) symmetry in e^+e^- annihilation processes leads to interesting predictions for the case of two-meson final states. Cross sections for annihilation into two charged pions and two charged kaons are equal, i.e.,

$$\sigma(e^+e^- \to K^+K^-) = \sigma(e^+e^- \to \pi^+\pi^-); \tag{1a}$$

annihilation into two neutral kaons is forbid-